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Sustainability: An integral engineering design approach

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ABSTRACT

The work described in this paper won an Engineering Award from the UNESCO and the United Nations. It qualified among the top 30 finalists from a pool of about 3200 engineering entries from the world's most prestigious universities in 89 countries, including Cambridge, Oxford, MIT, Stanford and Yale. This paper describes the methods employed in a sustainability project titled 'Global Basic Needs in an Integrated Sustainable Approach' submitted by the author to the UNESCO in agreement with the United Nations Millennium Goals and within their framework of the Mondialogo Engineering Award. A six-nation international jury of renowned leading scientists and engineers selected this project for a nomination award. While we all anxiously wait for science to provide the solutions to global warming and catastrophic climate change, a holistic engineering approach was used to halt pollution, and to provide sustainable shelter, clean water, energy, food and education to the global population. This approach can be used anywhere in the world and conceptualizes a revolutionary sustainability paradigm for present and future societies. This work is a contribution to the advancement of the science of sustainability everywhere on the planet.

Contents

1. Introduction

Sustainability is solely an inherent property of natural ecosystems, in which there is mass and energy balance [1]. It is misleading to believe that a resource such as a crop is sustainable only because it is renewable. Many crops used for human consumption are renewable only with a large input of resources [2]. Hence, it can be safely stated that human sustainability is possible only when it follows natural laws of mass and energy balance, and is, therefore, an extremely complex issue. The reasons for this complexity are clearly owing to its direct connections to the natural systems of the planet – air, water, soil and sunlight – that sustain and make all life possible. These elements are intrinsically and inextricably interconnected in an entropic cycle of life and death, and in a permanent state of flux. Extensive scientific studies on the human consumption of global resources have been done in recent decades that clearly confirm that the human species is on a brutal collision course with its natural environment [3–6]. Two fundamental studies that quantify the extent of human unsustainability are mentioned here. The first is Vitousek et al.'s seminal work on the human appropriation of the products of photosynthesis done at Stanford University [7], and the second, the revolutionary 'human footprint' calculations by Rees and Wackernagel at the University of British Columbia [8]. These two studies led the work to the rigorous scientific calculation of the human species impact on its environment. In spite of scientific advances, global consumption continues at ever increasing rates to this day, and not much progress has been achieved to halt and reverse the effects of the unsustainable use of resources by the ever increasing human population [9]. The consumption driven modern way-of-life continues un-abated in all fronts, everywhere. Therefore, other approaches need to be explored. A holistic approach that uses an

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integral engineering method to provide for the primary needs of the population – shelter, water, food, energy and education – is detailed in this work. This method takes into full account the conservation of mass and energy of the natural ecosystems.

The project main intent was to offer a solution to the overall improvement of the living conditions of the over 3 billion of the world's population mostly in undeveloped countries who have no access to clean water or food [10,11]. About 3.7 billion people, i.e., more that half of the current world population are malnourished, according to data published by the World Health Organization. The design approach consists of eight major components integrated into a fully-functional system designed to work in harmonious symbiosis with the living environment: passive solar shelter with rainwater catchment system, pre-filtering and cistern, solar energy for lighting, hot water and cooking, compost toilets with urine separation, mini-marsh greywater system, and an organic garden and compost bin.

2. Integral design method

The general approach to sustainability is generally deeply flawed. Its main answer consists typically at throwing a perceived 'green' solution – e.g., wind, hydrogen, biomass, nuclear or solar energy – to real world problems – water, waste, food or energy – in one single plug-in format to existing systems, while leaving all other existing issues associated with the un-sustainable existing structures untouched and in place. The underlying causes of the existing environmental, health and socio-economic problems are left intact for most cases, therefore the insignificant amount of progress that has been achieved after decades of struggle towards a sustainable society. Sustainability solutions addressing the needs of society and its use of resources must take on a whole systems analysis, and subsequently, a whole systems implementation. Nature and human interactions with the natural environment cannot and should not be seen as isolated from each other.

To obtain a clear perspective, it is best to enter sustainability from the back door, i.e., to first take a glance at what is not sustainable. With less than 5% of the world's population, the United States consumes about 1/3 of the world's resources, many of which are already overexploited [9–11]. Elementary algebra says that three countries with the same size of the U.S. and consuming at the same rate as the U.S. does, would consume 100% of everything. That would also mean that less than 15% – about 1/7 – of the world's population would consume all of the world's resources at those rates (see Figs. 1 and 2). Europe, with a population comparable to that of the U.S., now consumes just about as much as the U.S. does, and gobbles another 1/3 slice. That leaves about 1/3 of the world's resources to be shared by well over 3/4 (85%) of the world's population. One more country the size of the U.S. consuming at the present U.S. consumption levels – which is not terribly difficult to imagine – and there will be nothing left to share. Elementary algebra again tells us that at current rates of extraction and consumption by developed countries, not one, two, three, four, five, or six, but just about seven planets with the same abundant resources – air, water, sunlight, trees, animals, plants, oil and soil – would be needed to sustain the current world population at industrialized living standards. In the end, we would leave those seven planets ozone depleted, warmed up, species extinct and inhabitable no doubt like we are doing to this one. Furthermore, with only about half of a percent of the world's total biomass, the human species manifests itself as an incredibly demanding species on its environment by gobbling up 50% of the global products of photosynthesis [7], see Fig. 3. Clearly, the planet has too many people for the available resources of land, water, and energy [46]. The current world population is about 6.7 billion and growing at 100 million each year. The demands of the current population are at a real-time 120% over and in excess of what the bio-capacity and regenerative systems of the planet can work out and therefore we are already depleting the natural stores of the planet at that ratio every second [8]. As seen above, at current levels of un-sustainable and nonsensical consumption, splurge and waste, the Earth carrying capacity is about one billion people. Less than 2 billion

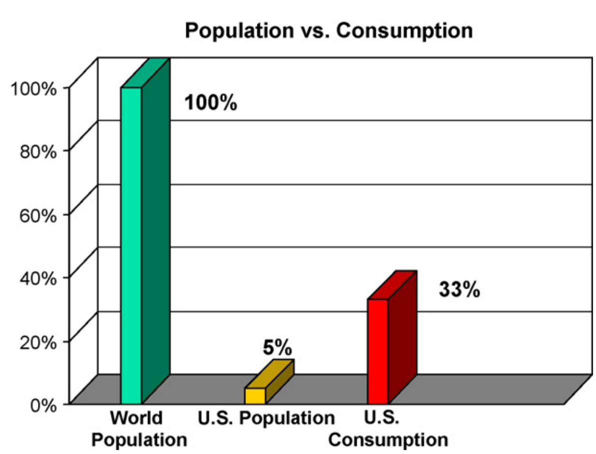

Fig. 1. U.S. population versus world consumption.

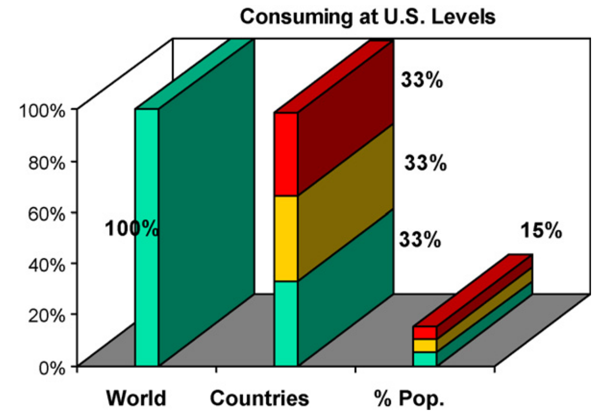

Fig. 2. Consumption at U.S. levels.

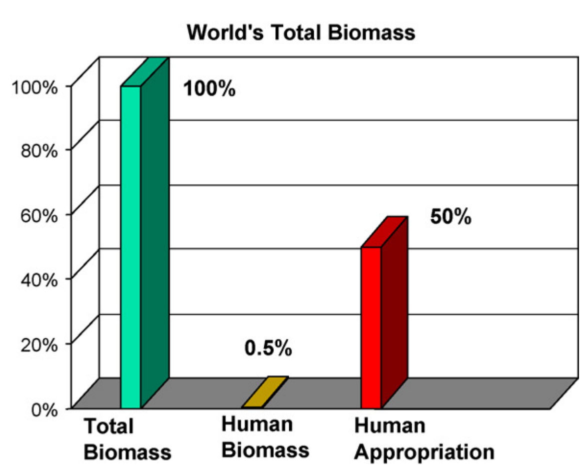

Fig. 3. With about half of 1% of the total biomass on the planet, the human species appropriates about half of the total products of photosynthesis. Clearly, doubling the current world population would entail one hundred percent appropriation of all the products of photosynthesis solely by the human race at current consumption levels.

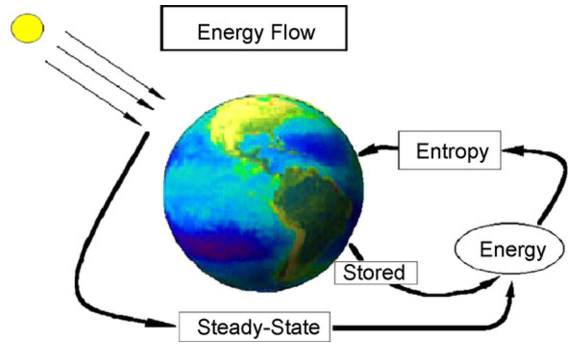

Fig. 4. Energy flow. Most world energy us is derived vast stores of 'buried sunshine,' i.e., coal, oil and natural gas. Once exhausted, energy used must revert to a steady-state use of sun energy.

is estimated for a sustainable human society where conservation and non-polluting lifestyles are adopted everywhere [46]. These simple, yet effective calculations should be sufficient to clearly put into perspective the brutal side of the human species current path of un-sustainability [7–11,46].

From the current total 15 TW of energy from all sources consumed by humans, the largest percentage is obtained directly from 'stored sunshine,' i.e., the energy contained in deposits of coal, oil and natural gas [9–11]. It took more than 700 million years for oil, natural gas, and coal to accumulate in a random geological boon process that is also extremely unlikely to happen again any time soon [2]. Once the Earth stored energy deposits are exhausted, with no indications at the moment that they will not be in addition to all the consequences that are becoming increasingly more evident such as global warming, the only other available option is to revert to a '*steady-state*' of energy consumption that relies on the energy directly obtained from the sun (see Fig. 4). In 1 h, the Earth receives as much energy from the sun as the global human energy consumption in one entire year from all sources. Therefore, a decentralized, local-economy based, self-sufficient and happy global human society is entirely possible. The economics of sustainable societies only recently have started to come to light in the works of prominent authors who dared to challenge the absurd theories of classic economics and its disastrous consequences [47,48]. The purpose of this work is to undertake the transition to a solar powered '*steady-state*' model immediately and without delay.

Addressing the basic needs common to all human beings – shelter, water, food and education – from an integral systems perspective where there is conservation of mass and energy is essentially the key to achieve mass and energy balance (see Fig. 5). Sunlight is converted into electrical energy to provide lighting required for reading and education. Sunlight is also used directly for solar cooking eliminating both the need to gather firewood and the pulmonary problems associated with smoke from fire inside the house. A solar cooker was designed directly into one of the sun facing house walls offering the convenience of a permanent appliance. Sunlight is also used to heat water for cleaning and washing. All the rainwater is collected by a catchment system and stored in a cistern for drinking and washing, and for garden use when it is sufficiently abundant. Water used in washing and cleaning is gravity fed to a mini greywater marsh and used directly in the organic garden afterwards. No chlorine, detergents, hard soaps or chemicals are allowed in this process. Human waste is composted in a compost toilet that eliminates the use of water and its associated sewer system. Solid wastes from food preparation and cooking are composted in a compost bin. The compost hence obtained is used directly in the organic garden to build the soil, create humus, soil fertility, provide fresh produce, fruits and vegetables and maintaining and replenishing the water table. Notice the circular arrow flow between solar cooking, solar hot water, greywater marsh, compost toilets, compost bin and organic garden going back to solar cooking which re-establishes the natural nutrient cycle required to sustain life (see Fig. 6). The eight main design elements are integrated into a whole functioning sustainable system, as follows:

I. Passive Solar House
II. Rainwater Catchment System, Pre-filtering & Cistern
III. Solar Energy & Lighting System
IV. Solar Domestic Hot Water System
V. Solar Cooking w/Backup High-Efficiency Wood Stove
VI. Compost Toilets w/Separate Urine Collection
VII. Mini-Marsh Greywater System
VIII. Organic Garden & Compost Bin

I. *Passive Solar House*: The main structure is built using ageless, natural and non-toxic materials that can be obtained locally and with thermal properties suitable for both cold and hot weather climates such as reinforced adobe, pressed earth block, or strawbale [12–15]. Local availability, material familiarity, economy and very low energy required for its production are the key factors for this selection. These building materials store solar heat during the day and release it slowly to the interior throughout the night during cold periods, thus providing temperature stabilization for the interior and thus avoiding the use of energy dependent heating or cooling by mechanical air conditioning systems. The structure is oriented in the East–West direction alongside its larger dimension following passive solar design guidelines, with dimensionally designed awnings, trellises and windows to take full advantage of latitude, insolation and prevailing winds [16–20].

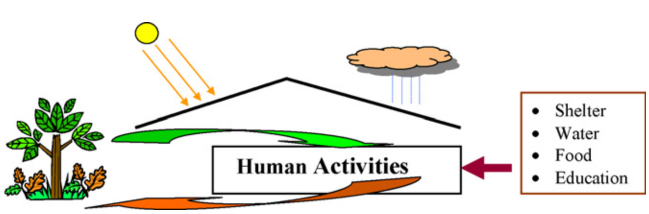

Fig. 5. Basic global human needs are shelter, water, food and education. They are required to support all human activity, which in turn must be supported by soil, water and sunlight on which we all depend.

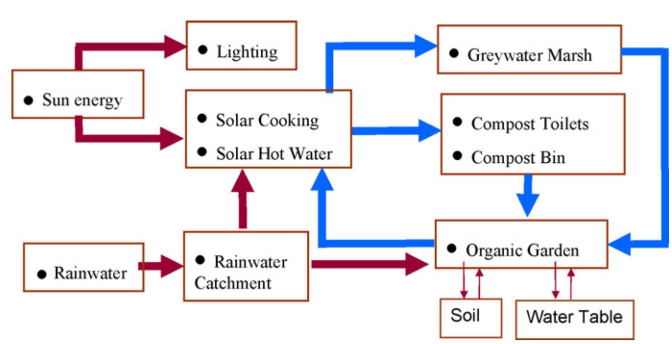

Fig. 6. The use of sun energy, water, food and wastes for sustained human activity. The circulation of water and solid waste to the organic garden and back to solar cooking in the form of food re-establishes the vital nutrient cycle (blue arrows). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

II. *Rainwater Catchment System, Pre-filtering and Cistern*: All the rainwater from the roof is collected. The rainwater is cleaned and pre-filtered from debris, and is stored in a cistern where it can be used primarily for drinking. Washing and irrigation uses are also acceptable when there is excess water from abundant rain [21–23]. About 25 l/m^2 of roof can be effectively collected for each cm of precipitation from rain. With a relatively small roof surface of about 100 m^2 and as little as 25 cm of precipitation annually common to many areas normally considered as being deserts, about 62,500 l of rainwater can be collected per year, by no means a small amount. While only a relatively small portion of the Earth enjoys plentiful rain precipitation, the water conservation and re-use methods employed throughout by the integral engineering design approach drastically reduce the amounts normally prescribed per capita, hence making the amount of collected water above very significant and suitable for many other uses in addition to drinking.

III. *Solar Energy & Lighting System*: Solar energy is captured from the roof with a set of photovoltaic panels (300 W total). Energy will be stored in a deep-charge battery to be used for interior lighting with compact fluorescents (5–13 W) and LED's (1–5 W). The solar energy system will provide about 1500 Wh/day in most climates, sufficient for most lighting needs required for educational purposes [24–26].

IV. *Solar Domestic Hot Water System*: Also on the north side of the house, a simple domestic batch solar hot water tank will be built to warm water for a low-flow solar shower and hand washing. No detergents, bleach, phosphates, commercial soaps or cleaners will be allowed in the system, only simple natural soaps that can be either fabricated or purchased locally [27].

V. *Solar Cooking w/Backup High-Efficiency Wood Stove*: On the north side of the house, a solar cooking oven will be built with access from the inside of the house for preparing and cooking hot meals [28]. This will mostly eliminate the use of firewood and the time required to gather it, and the devastation to wild forests that comes with this practice [10,11]. For cloudy days when the sun does not shine, a backup wood stove of a snug design and high-efficiency combustion chamber will be constructed inside the house [29,30].

VI. *Compost Toilets w/Separate Urine Collection*: A composting toilet with separate urine extraction will be built in the home. Composting toilets do not use or pollute water, thus conserving a huge amount of the precious life-giving liquid vital for other uses. Human waste and urine are a vital resource [31–34]. Urine collection diluted with greywater will be used in the garden to provide additional irrigation and fertilizer (3–3–3 NPK). When properly composted to a ratio of about 30 parts of carbon (about one coffee size can of shredded leaves, sawdust, etc. added to the compost toilet after each use) to one part of nitrogen present in human waste, the temperature in the compost toilet pile will raise to about 55–75 °C and will kill all the pathogens present in human waste [32]. The humus produced in this process can safely be used in the organic garden outside to build-up and enrich top-soil, re-establish the nutrient cycle, improve soil fertility, eliminate the need for municipal sewer systems and its associated problems of pollution of rivers, waterways, rivers and streams, and to grow fresh food, fruits and vegetables required for healthy nutrition and dietary needs of the population. This arrangement is both suitable to rural and city areas as demonstrated by the recent opening of the 2800 m^2 C.K. Choi office building at the University of British Columbia, Vancouver, Canada that is *not* connected to the municipal sewer system.

VII. *Mini-Marsh Greywater System*: Water used in washing is directed to a mini greywater marsh system where it is pre-filtered from grease and solid debris. The roots of cattails and bulrushes filter the remaining nutrients in suspension and build plant life with very low or no vector problems. The cleaned water is used for irrigation in the organic garden. Only a handful of plant species adapted to the region are required in this mini-marsh, mostly from the cattail family or equivalent [35,36].

VIII. *Organic Garden & Compost Bin*: The organic garden is built using organic and bio-intensive methods. Heavy soil mulching can cut the amount of water usage up to 75% when compared to wasteful conventional irrigation methods. Using closely spaced, multicroping, and green crops creates and maintains soil fertility and completely eliminates the use of fossil fuel dependent chemicals, fertilizers, pesticides and herbicides [37–39]. The organic garden is designed with swales on

Fig. 7. The integral sustainable engineering design approach. North orientation in the south hemisphere, and vice-versa. All elements work in symbiosis and harmony to clean the water and air, re-establish the nutrient cycle by processing human waste, and support life.

contour along the natural slopes of the plot terrain to catch all the ground running water from rains, and heavily mulched to prevent water evaporation and allow the slow permeation of water into the local water table [40]. A compost bin is built to compost the garden wastes from crop rotations and other vegetable wastes coming from the house and the kitchen such as fruit skins, waste paper and vegetable peels. The organic compost obtained from the composting toilets in addition to the compost obtained from a compost bin will be used in the organic garden [32,37]. Expected yields of fruits and vegetables using bio-intensive cultivation methods are about 15 kg/m^2 per year, or about 60 metric tons per acre per year, well above what is obtained from chemical 'conventional' methods [37,38]. Additionally, a 75% reduction in irrigation water use is also expected due to the higher moisture retention of mulched organic soil, and the additional benefit that there will be no land, people, water, air or animal exposure to the risks of toxic pesticide use and contamination, and its associated pollution of waterways [41]. Considering that the average meal travels about 1500, 5000 and 6800 miles to arrive at the American, Canadian and Japanese tables, respectively, and that it takes about 10 calories to produce one calorie of the food we eat today, the reverse of what was required just a short 50 years ago [41–45], the soil is the place where it all comes together – air, water, sunlight – into the magic of life, and the most significant aspect of the project (see Fig. 7). Only the most profound humbleness can truly appreciate the unfathomable and awesome symbiosis that coalesces in all that is alive and aware in the natural world.

3. Conclusions

The recognition given to this project by the world community and the distinguished international jury signifies a very welcome worldwide shift in awareness and critical thinking towards sustainability. The change to a sustainable way of life is required everywhere without delay if our species is anything but serious about its own future in this far corner of the universe. We looked at the system design from an integral point of view, not just as a combination of isolated plug-in components. From a systems perspective, the cycle is closed. Food, water, air and sunlight are used in a continuous entropic cycle that works in support of human activities, and vice-versa. There is no waste, and additional inputs of energy or resources should not be required. A sustainable system designed in this fashion is therefore autonomous, self-sufficient, self-regenerating, completely independent of distant resources and fossil fuels, and in stark contrast with current uncontrolled consumerism.

A significant purpose of this project is to serve as a multi-disciplinary research platform to obtain rigorous scientific data validating the integrated sustainability approach for publication in worldwide access peer-reviewed journals, to model sustainability, to spread appropriate engineering knowledge to effectively combat and stem man-made climate change and global warming, achieve global security, education and energy independence, and to establish and develop the science of integral sustainable systems engineering, design and development.

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